AD-A239 943

(2)

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT ~~As it appears on the report~~ Unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) 026845-910719	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 91 0698
6a. NAME OF PERFORMING ORGANIZATION University of Michigan Ultrafast Science Laboratory; 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION AFOSR
6c. ADDRESS (City, State, and ZIP Code) 1006 IST Building, 2200 Bonisteel, Ann Arbor, MI 48109-2099	7b. ADDRESS (City, State, and ZIP Code) Building 410, Bolling Air Force Base, Washington, D.C. 20332-6448
8a. NAME OF FUNDING/SPONSORING ORGANIZATION AFOSR; 8b. OFFICE SYMBOL (If applicable) NE	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR-90-0214
8c. ADDRESS (City, State, and ZIP Code) Building 410, Bolling Air Force Base, Washington, D.C. 20332-6448	10. SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO. 61103D; PROJECT NO. 3484; TASK NO. A3; WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification) Transport in Heterostructures & Devices in Microwave and Millimeter-Wave Regimes

12. PERSONAL AUTHOR(S) Gerard A. Mourou, John F. Whitaker, Theodore B. Norris

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Annual Report	FROM 4-1-90 TO 3-31-91	1991 July 19	18

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	ultrafast optics, high-speed electronics, electron transport in solids, resonant tunneling, time-resolved RHEED, fast modulators, fast detectors, LT-GaAs, ballistic transport
09/05			

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Transport phenomena has been studied in semiconductors and superconductor materials, and devices using ultrfast optical and electrical signals. Femtosecond optical absorption spectroscopy has been used to study the carrier dynamics in LT-GaAs. Optical techniques have also been used to observe for the first time the ballistic acceleration of electrons from the band edge in a GaAs quantum well and the domain formation in superlattices as well as excitonic transport in quantum wells. Using LT-GaAs ultrafast electrical signals, less than one picosecond in duration have been produced with amplitude up to one KV. These pulses have a frequency spectrum extending to one THz and have been used to study the physics of semiconductors and semiconductor devices in the high-field and high-frequency regime.

Using LT-GaAs photoconductive switches, and in conjunction with the electro-optic sampling we built an electro-optic analyzer capable of extracting S-parameters of active devices, up to 100 GHz. These techniques have been applied for the measurement of the fastest photoconductive response times of GaAs and In-GaAs epitaxially grown at 200°C. In addition, a new technique

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclass
22a. NAME OF RESPONSIBLE INDIVIDUAL Witt	22b. TELEPHONE (Include Area Code) 202-767-4931; 22c. OFFICE SYMBOL NE

DD Form 1473, JUN 86 — Previous editions are obsolete. — SECURITY CLASSIFICATION OF THIS PAGE

Report 026845-910719

TRANSPORT IN HETEROSTRUCTURES AND DEVICES IN MICROWAVE AND MILLIMETER-WAVE REGIMES

Gérard A. Mourou
John F. Whitaker
Theodore B. Norris
University of Michigan
Ultrafast Science Laboratory
1006 IST 2099
2200 Bonisteel
Ann Arbor, MI 48109-2099

A-1

19 July 1991

Annnual Report for Period 1 April 1990 to 31 March 1991

Unclassified

Prepared for:

Dr. Gerald Witt
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
Building 410
Bolling Air Force Base
Washington, D.C. 20332-6448

Abstract

Transport phenomena has been studied in semiconductors and superconductor materials, and devices, using ultrafast optical and electrical signals. Femtosecond optical absorption spectroscopy has been used to study the carrier dynamics in low-temperature epitaxially grown (LT) GaAs. Optical techniques have also been used to observe for the first time the ballistic acceleration of electrons from the bandedge in a GaAs quantum well and the domain formation in superlattices as well as excitonic transport in quantum wells. Using LT GaAs ultrafast electrical signals, less than 1 ps in duration, have been produced with amplitude up to 1 KV. These pulses have a frequency spectrum extending to 1 THz and have been used to study the physics of semiconductors and semiconductor devices in the high-field and high-frequency regime.

Using LT GaAs photoconductive switches, and in conjunction with the electro-optic sampling we built an electro-optic analyzer capable of extracting S-parameters of active devices, up to 100 GHz. These techniques have been applied for the measurement of the fastest photoconductive response times of GaAs and In-GaAs epitaxially grown at 200°C. *In addition, a new technique* has been devised for performing coherent time-domain spectroscopy of dielectrics, semiconductors, and thin-film superconductors, using terahertz bursts of radiation. The complex conductivity of high-temperature superconductors has been measured.

The LT GaAs has also led to an important new ultrafast detector with a bandwidth of 375 GHz and excellent responsivity. Laser oscillators are of extreme importance for our program. We have worked on a new high-average power, low-noise oscillator-based on titanium sapphire. This laser is now producing less than 100 fs with ten times the power of a colliding pulse mode-locked laser and very good noise figures.

Technical Report

In this section we describe some of the scientific achievements accomplished this year.

1. Low-Temperature Epitaxially Grown (LT) GaAs Dynamics

When GaAs is grown by MBE at substrate temperatures around 200 ^{o}C, the carrier lifetime is reduced to the subpicosecond regime. The most direct way to probe carrier populations is via optical absorption spectroscopy. Femtosecond white light absorption spectroscopy was used to probe the carrier relaxation dynamics near the bandedge of LT GaAs. The transient absorption spectrum at the bandedge gave the carrier lifetime directly. A series of LT GaAs samples was grown at Cornell University, under various growth conditions (substrate temperature ranging from 180 to 210 ^{o}C, and arsenic pressure ranging from 4 x 10^{-6} to 1.5 x 10^{-5} Torr). The lifetime was found to be subpicosecond in all cases, showing a weak dependence on the growth conditions. As expected, the lifetime decreased with decreasing growth temperature, but surprisingly increased with higher arsenic pressure (Fig. 1-2). TEM analysis of the sample microstructure was done at Berkeley by Z. Liliental-Weber and E. Weber. Our results appear to be most straightforwardly interpreted in terms of arsenic precipitates being responsible for the ultrafast lifetime. Using femtosecond time-resolved-reflectance techniques, we have measured a subpicosecond (<0.4 ps) carrier lifetime for GaAs materials grown at ~200°C by MIT Lincoln Laboratory and Cornell University. Using the Lincoln material, 0.6-ps full-width-half-maximum electrical signals have been generated via photoconductive switching and measured by both electro-optic and photoconductive sampling. Good responsivity has been observed, corresponding to a mobility value of ~120-150 cm^2/V-s for the photogenerated carriers. The material is also semi-insulating, making it an ideal material for a number of subpicosecond photoconductive applications.

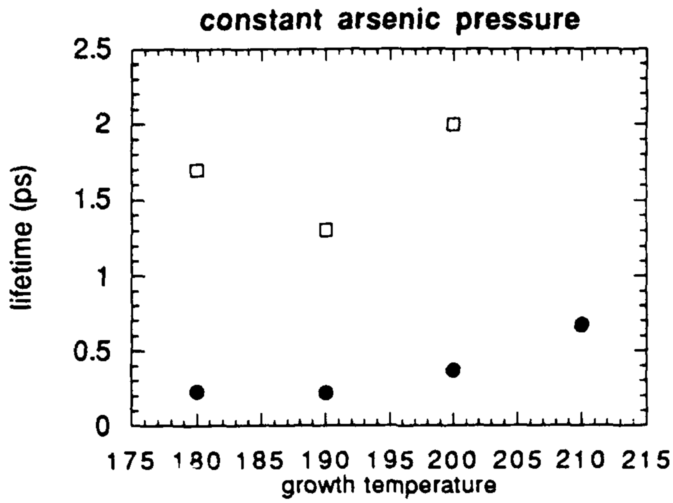

Fig.1. Fast and slow components of the carrier lifetime at the band edge of LT GaAs as a function of growth temperature (for arsenic pressure = 8×10^{-6} Torr).

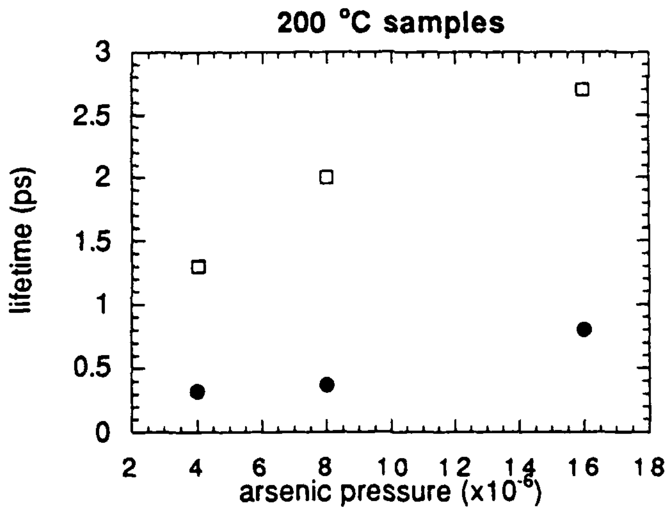

Fig.2. Fast and slow components of the carrier lifetime of LT GaAs for a fixed growth temperature of 200°C.

2. Time-Resolved Ballistic Carrier Dynamics

The principal advantage afforded by optical absorption spectroscopy is that it provides the time-dependent energy distribution functions of the carriers in semiconductors. We have extended the techniques of femtosecond pump-probe spectroscopy to the study of transport in GaAs bulk and quantum wells in high (up to 16 kV/cm) electric fields. In these experiments, carriers are photo-injected at or near the band

edge, and are accelerated by an externally applied electric field. Initial experiments on bulk GaAs displayed the carrier acceleration effect, and showed the importance of injecting the carriers *at* the band edge (*i.e.*, with zero initial kinetic energy).

Experiments on GaAs quantum wells, with photoexcitation resonant with the exciton, in the presence of a strong electric field *parallel* to the QW planes, showed quite clearly the ballistic acceleration of electrons from the bandedge. These electrons appear as a nonthermal high energy tail on the differential absorption spectrum (Fig. 3). The time scale of the ballistic acceleration was shown to be about 150 fs (Fig. 4). Interesting effects due to ultrafast exciton field-ionization, electron-hole scattering, and electric field relaxation due to accelerated space charge were observed. These topics are under further study, with an emphasis on enhancing ballistic effects by using higher electric fields and lower photoexcitation levels. It should be noted that these experiments constitute the first observation to our knowledge of the ballistic *acceleration* of electrons in an externally applied electric field in a semiconductor. They also provide a novel way of probing the complete dynamics (i.e. carrier distributions and total time-dependent electric field) of photoconductive switching.

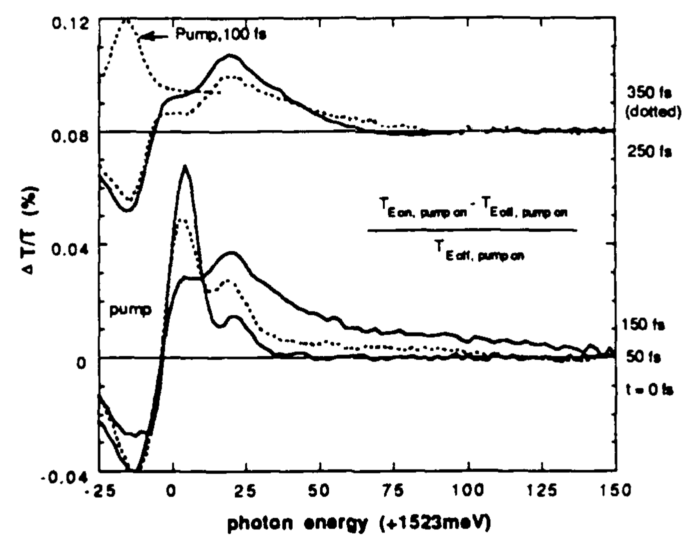

Fig. 3. Differential transmission data for quantum wells in a strong in-plane electric field, with carriers photo-injected at the band edge. The high energy tail at 150 fs is due to electrons ballistically accelerated from the band edge.

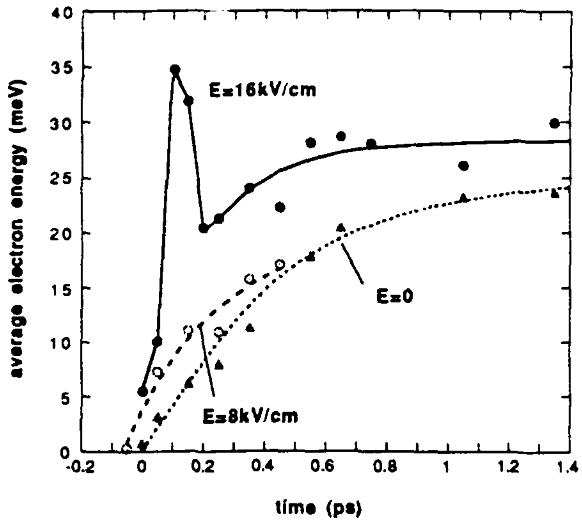

Fig.5

Fig. 4. Average energy per electron with and without electric field. For zero field, the electrons warm up from 0 to 25 meV (300 K) in about 1.4 ps. With a strong electric field, the electrons rapidly gain energy, followed by an overshoot due principally to rapid relaxation of the total electric field.

3. Coherent Time-Domain Mobility Measurement

The study of the physics of transport in semiconductor devices requires one to be able to measure directly the time-dependent velocity (or, correspondingly, the mobility) of electrons under the conditions of high electric fields and at high frequencies. The experimental challenge is to rapidly (i.e. on a subpicosecond time scale) apply a strong (> 10 kV/cm) electric field to the semiconductor structure of interest, and to monitor the response of the electrons to the applied field. In the past year we have begun an approach to this problem using a "coherent time-domain mobility" technique. A photoconductive switch is used to generate a terahertz-bandwidth pulse, which propagates down a transmission line. LT GaAs is generally used for the photoconductive switch material, since its unique properties of high dark resistivity, high responsivity, and fast lifetime make it possible to generate high-field pulses of the requisite bandwidth. The structure under study is integrated into the transmission line, so that (using electro-optic sampling) the incident, reflected, and transmitted voltage pulses through the structure may be measured.

Initial experiments have been performed on three structures: doped bulk GaAs, modulation-doped GaAs quantum wells, and a photo-injected plasma in LT GaAs. In all cases, we observe strong attenuation of the electrical pulse, as well as possible phase shifts. The data have been Fourier-transformed to look at the response in the frequency domain. Further experimental refinements are necessary to minimize the effect of reflections, and to facilitate interpretation of the data. We have begun modeling the

experiment, using transmission line propagation codes to model the pulse propagation, and a Monte Carlo code to model the transient carrier response, in order to interpret the data in terms of field and frequency-dependent response of the carriers.

4. High-Voltage Switching

As mentioned previously, LT GaAs has extraordinarily high-dark resistivity, and a concomitantly high-breakdown threshold. Nevertheless, it is an efficient photoconductor. This combination of properties makes it uniquely suited to high-voltage photoconductive switching. We have demonstrated for the first time the switching of kilovolt-level pulses on a single-picosecond time scale by photoconductively switching an LT GaAs switch.

The device used consists of 100-mm-wide gold coplanar striplines separated by 100 mm and deposited on an LT GaAs substrate. These lines are pulse-biased at 1.3 kV for about 400 ps using a separate 4-mm Cr:GaAs photoconductive switch. An amplified 100-fs dye laser pulse (of energy ≤ 1 mJ) shorts the lines together to produce an electrical transient, which is measured 300 mm from the switch to be of 850-V, 1.4-ps risetime, and 4-ps duration (implying a subpicosecond rise time and > 1-kV amplitude at the switch) (Fig. 5). This result represents the highest voltage ever switched on the single-picosecond time scale. This new capability to produce picosecond high voltage and high-field electrical pulses is of interest for applications in fields such as nonlinear millimeter-wave spectroscopy, high-field physics, radar, and ultrafast instrumentation.

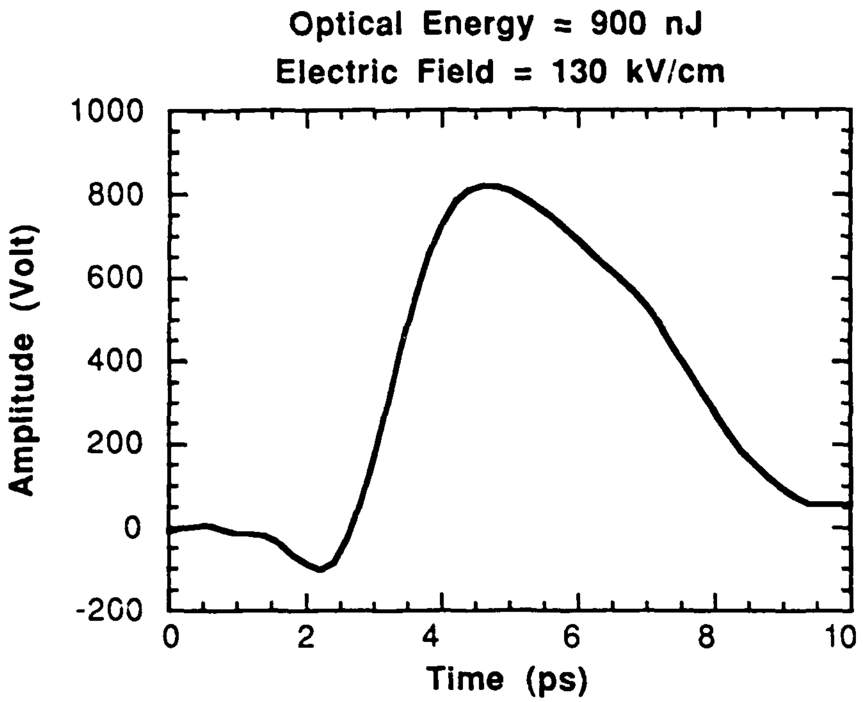

Figure 5

5. Field Domains in Superlattices

When a superlattice (SL) is biased by a perpendicular electric field, and carriers are present in the SL at moderate to high density, the field inside the SL will be nonuniform, and will consist of domains characterized by the alignment of levels in neighboring wells leading to sequential resonant tunneling. The generality of this phenomenon makes it an important topic of study, since all devices based on SL's will be affected by domain formation.

The techniques of Raman scattering by intersubband transitions and cw and time-resolved photoluminescence (PL) were used to investigate domain formation in undoped GaAs/(Al,Ga)As SL's, where the carriers were generated by means of photoexcitation. The Raman results show a strong correlation among intersub-band spectra, PL, and transport data. In particular, the intensity of the electronic scattering strongly decreases near the onset of current plateaus associated with the disappearance of domain boundaries. The smooth variation of the intensity during the transition from the two-domain to the one-domain regime suggests that there is a deficiency of holes at the domain boundary. Data as a function of power density suggest that resonant tunneling requires alignment of charge-density excitation. The time-resolved PL data provides very important information on the dynamic aspects of domain formation. The PL spectra were monitored after application of

a voltage step function on the sample. The low field domain always appears in the early stage and the system gradually evolves into the two-domain regime. Presently, we do not have a complete understanding of the transient behavior, but it is interesting that the observed domain formation times (≈ 60 ns) are significantly longer than the well-to-well transit times as measured in QW's of similar parameters.

6. Subpicosecond Pulse Propagation & Electro-Optic Network Analysis

Since progress in modern semiconductor device research has advanced response frequencies above 400 GHz, the bandwidth available from purely electronic test instrumentation has been exceeded. A lack of convenient and accurate high-bandwidth device characterization methods imposes a serious obstacle to progress in semiconductor device development and utilization.

We have combined the electro-optic sampling technique with the use of high-bandwidth coplanar strip transmission lines for the extraction of small-signal S-parameters of an active device. This technique enables one to determine device characteristics to a frequency of 100 GHz without extrapolation. First, experimental results for the propagation of subpicosecond pulses on coplanar structures were obtained and modeled using an algorithm that considered numerous loss and dispersion mechanisms. For terahertz bandwidth pulses, the modal dispersion and radiation losses were determined to be the dominant pulse-distortion mechanisms. This information allowed us to generate and measure the ultrashort electrical pulses to be input to the device under test (DUT) several millimeters from the DUT, so that the incident and reflected time-domain waveforms could be time-windowed, and then shift the measurement plane up to the device input.

Included in the devices that were measured was a 0.15-mm-gate-length pseudomorphic heterojunction FET supplied by General Electric's Electronics Lab. Its design is different from conventional high-electron-mobility transistors in that an AlGaAs/GaAs superlattice is used below the channel to improve carrier confinement. An additional planar doped layer in the strained channel improves charge density, which more than compensates for a somewhat lower mobility. The f_{max} for this device was modeled at GE to be in excess of 100 GHz.

The reflection (S_{11} and S_{22}) and transmission (S_{21} and S_{12}) S-parameters were obtained from the ratios of the Fourier transforms of the reflected, transmitted, and input waveforms from both the gate and drain sides of the device. Thus extracted from the measurements, the electro-optic S-parameters are plotted to 100 GHz (S_{21} is shown in a polar plot in Fig. 6, where x indicates the conventional rf network analyzer parameters

measured to 40 GHz). An excellent agreement was found in the comparison of the two measurements.

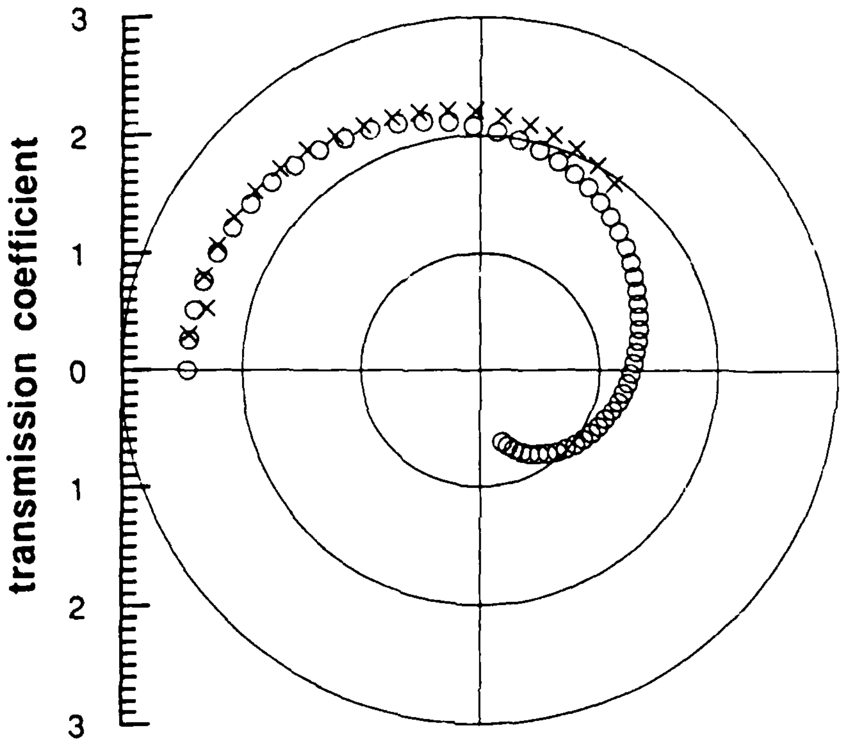

Figure 6

7. Terahertz Spectroscopy and High-Temperature Superconductors

Coherent time-domain spectroscopy is proving to be an extremely powerful tool in the study of the millimeter-wave and submillimeter-wave properties of materials. Thus far it has been applied to a number of material systems including dielectrics and semiconductors. This technique, like more conventional techniques such as Fourier-transform infrared (FT-IR) spectroscopy, is very broadband. Unlike FT-IR spectroscopy this time-domain technique is a coherent one, *i.e.*, both phase and amplitude information are obtained directly from the measurements. Thus far we have demonstrated coherent time-domain spectroscopy to have the ability to accurately measure complex index of refraction changes of less than 2% over a bandwidth exceeding 2 THz in thin samples (0.5 mm).

The terahertz radiation used is generated by momentarily shorting a dc-biased photoconductive switch with a short laser (pump) pulse. This switch is located at the center

of a simple dipole antenna imbedded in a coplanar transmission line. Hyperhemispherical dome lenses aid in the coupling of the radiation into the air and back onto an identical detector, and they provide collimation of the terahertz beam. The amplitude and temporal profile of the received signal is measured via photoconductive sampling. The addition of a continuous flow cryostat has given us the ability to cool samples to ~10 K.

Studies of the high-frequency properties of superconducting materials based on their response to millimeter- and submillimeter-wave electromagnetic perturbations are of special interest. They can give insight into the nature of quasiparticle excitations and pairing mechanisms, as well as a direct assessment of how the materials would perform as passive microwave devices (*e.g.*, interconnects, resonators, filters, *etc.*). The latter is found via measurements of the complex conductivity or surface impedance.

Such measurements of the real and imaginary parts of the complex conductivity of a high-T_C superconductor have been made by placing a $YBa_2Cu_3O_{7-x}$ sample deposited on MgO in the terahertz radiation between the antennas. The time-domain response was measured as the temperature was decreased from above T_C to below T_C. The complex conductivity obtained from the transmitted waveforms is shown in Fig. 7, where, as expected, there is a large contribution from superconducting paired electrons below T_C, but none above T_C.

Considering these measurements and others we have made on magnesium oxide and *p*-doped silicon, the coherent time-domain spectroscopy technique should prove to be an indispensable tool for the assessment of the terahertz properties of a wide variety of materials.

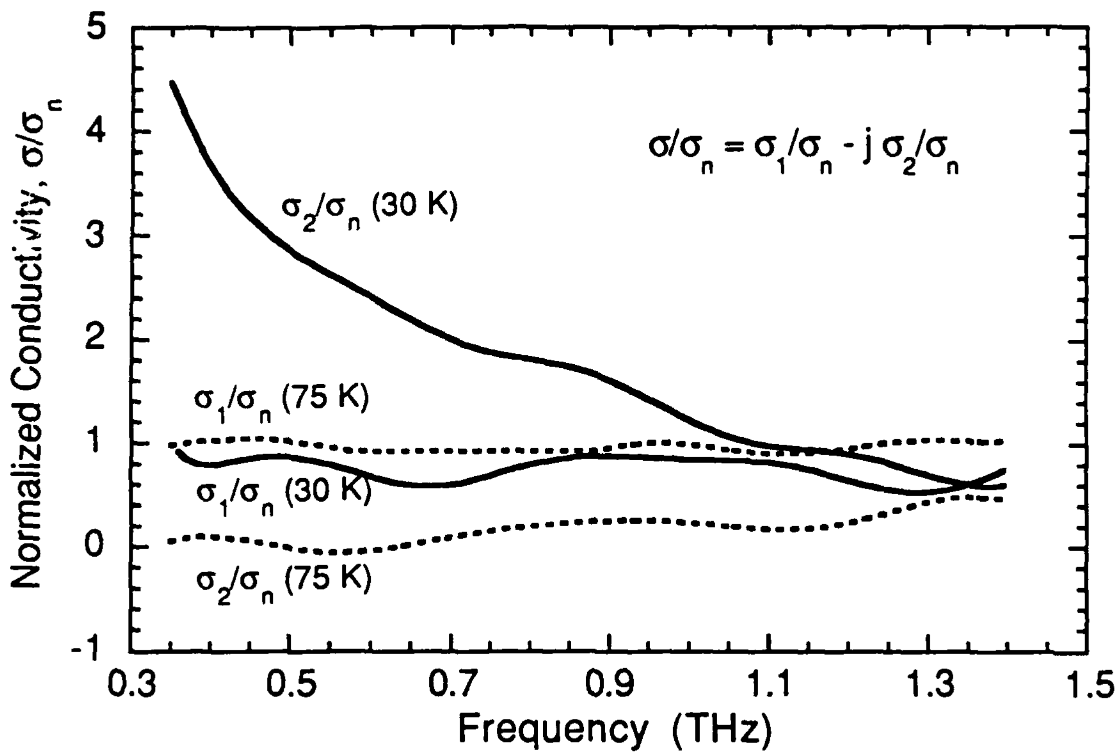

Figure 7

8. Development of a 375-GHz Photodetector

We have developed a novel 375-GHz bandwidth photodetector. The device is based on low-temperature epitaxially grown (LT) GaAs. The speed of the detector is determined by the carrier lifetime of the LT GaAs epilayer which is ~500 fs. Its high responsivity of 0.1A/W, on the other hand, results from matching the carrier transit time across the semiconductor to the carrier lifetime. A transit time of approximately 1 ps corresponds to the electrode spacing of 0.2 μm used in this preliminary work. The detector also maintains its ultrafast response even when the optical pulse energy exceeds 10 pJ. Figure 1 shows a family of traces taken with the pulse energy spanning nearly three orders of magnitude. We see that with a pulse energy of 21 pJ the detector is driven from its 10^7 Ω off-state resistance down to 30 Ω. This result highlights the unique dual functionality that is possible with this picosecond photoswitch. We can now integrate efficient detectors, gates, and pulsers and apply the technique of semiconductor autocorrelation to measure ultralow-intensity optical (or perhaps x-ray) signals of single-picosecond duration (Fig.8).

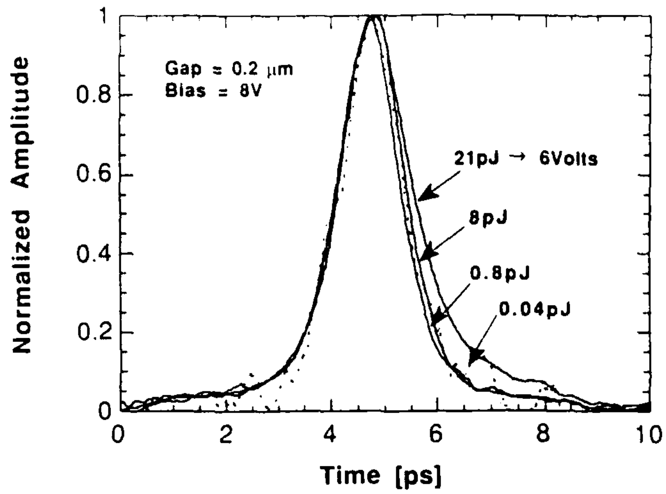

Figure 8

9. Laser development:

The measurement of ultrafast electrical signals using the electro-optic sampling technique or the detection of very small transient absorption changes in semiconductors is currently limited by the attainable signal to noise ratio. Different complicated ways have been explored to decrease the noise of femtosecond dye lasers/amplifiers currently used in those experiments. In order to provide experimentalists with a more reliable and more versatile source, we have developed a new femtosecond oscillator based on a solid-state laser medium: titanium doped sapphire. We used a linear, astigmatically compensated, resonator including a pair of prisms for group velocity dispersion compensation. This laser is pumped by a cw argon-ion laser. It produces 70-fs pulses and is presently tunable from 730 nm to 890 nm. Longer wavelength should be attainable by using another set of mirrors. The average power produced by this laser is 10 to 50 times higher than the usual power obtained with a femtosecond dye laser. We obtained up to 500 mW in a 80-MHz train of 70-90-fs pulses. We have studied the mode-locking mechanism leading to these short pulses and we believe that self-focusing in the laser rod along with the introduction of an aperture in the cavity makes the loss of the cavity higher for low intensity (long duration) pulses than for high-intensity (short-duration) pulses. This phenomena pushes the laser to run in the mode giving the highest intensity in the very short pulse regime. Since the laser medium is solid state and has a much longer upper state lifetime than this, the noise of this laser is much smaller than that of the femtosecond laser. The high-average power and the very good noise characteristics of these lasers are very important in our applications. Furthermore the fact that they are tunable around 800 nm is an advantage for semiconductor studies.

Publications

J.M. Chwalek, C. Uher, S. Gupta, J.F. Whitaker, and G.A. Mourou, J. Agostinelli and M. Lelental, "Femtosecond Optical Absorption Studies of Nonequilibrium Electronic Processes in High-Tc Superconductors," *Ultrafast Phenomena VII*, (Springer-Verlag Berlin 1990) pp. 351-353.

S. Gupta, J. Pamalapati, J. Chwalek, P.K. Bhattacharya, and G. Mourou, "Subpicosecond Photoconductivity in III-V Compound Semiconductors Using Low Temperature MBE Growth Techniques," *Ultrafast Phenomena VII* (Springer-Verlag, Berlin, 1990) p. 297-299.

J.M. Chwalek, C.Uher, J.F. Whitaker, and G.A. Mourou, J. Agostinelli and M. Lelental, "Femtosecond Optical Absorption Studies of Nonequilibrium Electronic Processes in High-Tc Superconducotrs," *Appl. Phys. Lett.* 57, 1696-1698, (Oct. 1990).

J.F. Whitaker, J.A. Valdmanis, M.Y. Frankel, S. Gupta, J.M. Chwalek, and G.A. Mourou, "External Electro-Optic Integrated Circuit Probing," *Microelectronic Engineering*, 12, 369-379, 1990.

M.Y. Frankel, J.F. Whitaker, G.A. Mourou, F.W. Smith, and A.R. Calawa, "High-voltage picosecond photoconductor switch based on low-temperature-grown GaAs," *IEEE Trans. Electron. Devices*, 37, 2493-2498 (Dec. 1990).

J. Shewchun, Y. Chen, J. Holder, and C. Uher, "Characterization of Y-Ba-Cu-O Superconductor Films on GaAs With a Al_2O_3 or $AlGaO_3$ Buffer Layer", *Appl. Phys. Lett.* 58, 2704, 1991.

A.B. Kaiser and C. Uher, "Thermoeletricity of High-Temperature Superconductors", *Studies of High-Temperature Superconductors* ed by A.V. Narlikar, (Nova Science Publisher, NY, 1991).

J.M. Chwalek, J.F. Whitaker, and G.A. Mourou, "Submillimetre Wave Response of Superconducting $YBa_2 Cu_3 O_{7-x}$ Using Coherent Time-Domainated Spectroscopy." *Electron. Lett.* 27, 447-448, (Feb. 1991).

M.Y. Frankel, J.F. Whitaker, G.A. Mourou, and J.A. Valdmanis, "Experimental characterization of external electrooptic probes," *IEEE Microwave Guided Wave Lett.*, 1, 60-62 (Mar. 1991).

J.M. Chwalek, C. Uher, J.F. Whitaker, G.A. Mourou, and J.A. Agostinelli, and M. Lelental, "Subpicosecond Time-Resolved Studies of Coherent Phonon Oscillations in Thin-Film $YBa_2Cu_3O_{6+x}$ ($x<0.4$)", *Appl. Phys. Lett.* 58, 980-982, 1991.

V. Sankaran and J. Singh, "Coherent Tunneling of Mixed State Hole Wave Packets in Coupled Quantum Well Structures", *Appl. Phys. Lett.* 58, 1509-1511, 1991.

Pending Publications:

S. Gupta, P.K. Bhattacharya, J. Pamulapati, and G. Mourou, "Optical Properties of High Quality InGaAs/InAlAs Multiquantum Wells", submitted to the *Journal of Applied Physics*, Sept. 1990.

J.M. Chwalek, C. Uher, J.F. Whitaker, and G.A. Mourou, "Subpicosecond Time-Resolved Studies of Coherent Phonon Oscillations in Thin-Film YBa_2Cu3O_{6+x} (x<0.4)", submitted to *Applied Physics Letters,* November 1990.

T. Motet, J. Nees, S. Williamson, and G. Mourou, "1.4 Picosencond-Risetime High-Voltage Photoconductive Switching", *Applied Physics Letters*, to be published (16 Sept., 1991).

S.H. Kwok, E. Liarokapis, R. Merlin, and K. Ploog, "Sequential Resonant Tunneling in Superlattices: Light Scattering by Intersubband Transitions", in *Light Scattering in Semiconductor Structures and Superlattices*, ed. by D.J. Lockwood and J.F. Young. (Plenum Press, New York, 1991).

S.H. Kwok, E. Liarokapis, R. Merlin, H.T. Grahn, H. Schneider and K. Ploog, "Raman Scattering Studies of Resonant Tunneling Domains in Quantum Well Structures", *Proceedings of the 20th International Conference on the Physics of Semiconductors*, ed. J. Joannopoulos. (World Scientific, Singapore, 1991).

Y. Chen, J. Nees, S. Wiliamson, "Propagation of Picosecond Electrical Pulses in GaAs for Velocity-Matched Modulators", to be published in *Picosecond Electronics and Optoelectronics*, ed. G. Sollner and J. Shah (Optical Society of America, Washington, D.C., 1991).

F. Salin, J. Squier, and G. Mourou, "Very Large Temporal Stretching of Ultrashort Pulses", submitted to *Applied Optics.*

W. Sha, T.B. Norris, W.J. Schaff, and K.E. Meyer, "Time-Resolved Ballistic Acceleration of Electrons in a GaAs Quantum-Well Structure", submitted to *Physics Review Letter.*

W. Sha, T.B. Norris, W.J. Schaff, and K.E. Meyer, "Time-Resolved Observation of Quasi-Ballistic Acceleration of Electrons in Quantum Wells", to be published in a special issue of *Semiconductor Science and Technology.*

T.B. Norris, W. Sha, W.J. Schaff, and X.J. Song, "Transient Absorption Studies of Low-Temperature-MBE-Grown GaAs", to be published in *Picosecond Electronics and Optoelectronics IV.*

Y. Chen, S. Williamson, F. Smith, and T. Brock, "375-GHz BandWidth Photoconductive Detector", submitted for publication in *Applied Physics Letter.*

Participating Professionals

Professional personnel who were associated with research being pursued under this contract were Professor Gérard A. Mourou, Dr. John F. Whitaker, Dr. Theodore B. Norris, Professor Janis Valdmanis, Dr. François Salin, J. Scott Coe, Dr. Donald P. Umstadter, John Nees, Dr. Philippe Bado, Professor Roberto Merlin, Professor Ctirad Uher, Professor Duncan Steel, and Steven Williamson. One Ph.D. was awarded during this period to Xiao Jue Song through Cornell University in January 1991 for a thesis titled: *Design, Growth and Fabrication of Resonant Tunneling Devices.* No other degrees were awarded.

Conference Presentations

J. Chwalek, C. Uher, S. Gupta, J. Whitaker, G. Mourou, J. Agostinelli, and M. Lelental, "Femtosecond absorption studies of nonequilibrium electronic processes in high-T_C superconductors," presented at the 7th International Conference on Ultrafast Phenomena, Monterey, CA (May 1990).

S. Gupta, J. Pamulapati, J. Chwalek, P.K. Bhattacharya, and G. Mourou, "Subpicosecond photoconductivity in III-V compound semiconductors using low-temperature MBE-grown techniques," presented at the 7th International Conference on Ultrafast Phenomena, Monterey, CA (May 1990).

J.F. Whitaker, "Ultrafast electrical device measurements," presented as a seminar at General Electric Electronics Laboratory, Syracuse, NY (July 1990).

S.H. Kwok, E. Liarokapis, R. Merlin and K. Ploog, "Light Scattering in Semiconductor Structures and Superlattices", ed. D.J. Lockwood and J.F. Young, invited paper at the *NATO Advaned Research Workshop on Light Scattering in Semiconductor Structures and Superlattices,* 1990, Mont Tremblant, Québec, Canada.

S.H. Kwok, E. Liarokapis, R. Merlin, H.T. Grahn, H. Schneider and K. Ploog, "Raman Scattering Studies of Resonant Tunneling Domains in Quantum Well Structures", presented at the *20th International Conference on the Physics of Semiconductors*, 1990, Thessaloniki, Greece.

W. Sha, T.B. Norris, W.J. Schaff, and K.E. Meyer, "Femtosecond Time-Resolved Studies of High-Field Parallel Transport in GaAs Quantum Wells", postdeadline paper presented at the *Quantum Optoelectronics Topical Meeting (Optical Society of America)*, Salt Lake City, March 1991.

T.B. Norris, W. Sha, W.J. Schaff, and X.J. Song, "Transient Absorption Studies of Low-Temperature-MBE-Grown GaAs", presented at the *Picosecond Electronics and Optoelectronics Topical Meeting (Optical Society of America)*, Salt Lake City, March 1991.

T. Motet, J. Nees, S. Williamson, and G. Mourou, "Picosecond High-Voltage Photoconductive Switching", presented at the *Meeting on Picosecond Electronics*, March 13-15, Salt Lake City, UT, 1991.

Y. Chen, J. Nees, and S. Williamson, "Propagation of Picosecond Electrical Pulses in GaAs for Velocity Matched Modulators", presented at the *Meeting on Picosecond Electronics and Optoelectronics*, March 13-15, Salt Lake City, UT, 1991.

M.Y. Frankel, J.F. Whitaker, G.A. Mourou, J.A. Valdmanis, and P.M. Smith, "100-GHz Electro-optic *S*-parameter characterization of high electron mobility transistors," presented as an invited talk at the Picosecond Electronics and Optoelectronics topical meeting, Salt Lake City, UT (March 1991).

J.M. Chwalek, J.F. Whitaker, and G.A. Mourou, "Low-temperature epitaxially-grown GaAs as a high-speed photoconductor for terahertz spectroscopy," presented at the Picosecond Electronics and Optoelectronics topical meeting, Salt Lake City, UT (March 1991).

C. Uher, J.M. Chwalek, J.F. Whitaker, G.A. Mourou, and J.A. Agostinelli, "Carrier-phonon relaxation rates in superconducting and insulating YBCO studied by femtosecond optical absorption," presented at the American Physical Society March Meeting, Cincinnati, OH (March 1991).

Y. Chen, S. Williamson, and T. Brock, "1.2 ps High-sensitivity Photodetectors/Switch Based on Low-Temperature-Grown GaAs'", presented as postdeadline paper at *Conference on Lasers and Electro-Optics (CLEO)*, May 13-17, Baltimore, MD, 1991.

T. Motet, J. Nees, S. Williamson, and G. Mourou, "Single Picosecond High Voltage Switching Using Low-Temperature-Grown GaAs", presented at the *Conference on Lasers and Electro-Optics (CLEO)*, May 12-17, Baltimore, MD, 1991.

Pending Conference Presentations:

Steel, Duncan G., "Nonlinear Optics and Quantum Wells", invited paper at the *Gordon Research Conference on Nonlinear Optics and Lasers*, July 22-26, Wolfeboro, NH, 1991.

Y. Chen, S. Williamson, T. Brock, F.W. Smith, and A.R. Calawa, "Multi-hundred Gigahertz Photodetector Development Using LT-GaAs'", submitted to *Material Research Society Fall Meeting (MRS)*, Dec. 2-6, Boston, 1991.

Y. Chen, S. Williamson, T. Brock, F.W. Smith, and A.R. Calawa, "Integrated High-Sensitivity Photodetector and Correlator with Picosecond Resolution", submitted to *IEEE International Electron Device Meeting (iedm)*, Dec. 8-11, Washington, D.C, 1991.